Slant path extinction in a stratified atmosphere

Andreas K. Goroch

Marine Meteorology Branch
Naval Research Laboratory
Monterey, CA 93943

1991

Introduction

Helicopter FLIR systems are used for detection and observation of ship targets in support of a variety of coastal naval operations. The coastal environment is complex with large scale conditions strongly modified by local variations of topographic and sea surface conditions. The ambient atmosphere is often stratified with different atmospheric layers characterized by substantially different moisture and signal propagation conditions. These conditions can strongly affect tactical operations.

This report describes the detection of a destroyer target by a standard helicopter FLIR during operational exercises in the Arabian Gulf. The observations show the detection range to be dependent on approach altitude, first increasing, then decreasing as altitude increases. This results suggests that the tactical user may have an optimal altitude for maximum detection range during FLIR operations. The altitude is potentially dependent on the characteristics of the target, the sensor, and the intervening atmosphere. We have developed a closed form model of detection range in a stratified atmosphere. This model is used to describe the

Figure 1. Detection range of destroyer using FLIR imager.

sensitivity of FLIR extinction to stratification and extinction characteristics of the atmosphere.

Observations

Structured FLIR detection runs were conducted during the SHAREM 115 exercise in the central Arabian Gulf on 23 and 24 April, 1996. A UH 60B helicopter was deployed with a standard FLIR imager during the exercise. FLIR performance was evaluated with a Spruance class destroyer, USS Caron, as a detection target. The destroyer moved at a steady speed of 5 knots to the northwest. The helicopter approached the destroyer first from starboard and then from the stern at different altitudes, ranging from 200 to 1500 ft. At each altitude, the helicopter would move away from the ship until the ship could no longer be seen on the video screen. The helicopter would the approach the ship until the target could be recognized as a warship. Detection was determined when the yardarms of the ship were distinguishable. Range was found from the ship radar, which provided ground range, the distance on the surface between the ship and the spot on the ocean directly under the helicopter. This procedure was completed for altitudes with first a starboard approach, followed by a stern approach.

The resulting ranges are shown in Figure 1 for the starboard and stern approaches. In general, the starboard approach had a longer detection range than the stern approach. This is obviously expected since the perceived cross section of the ship is greater in a beam approach. Both approaches showed a consistently longer detection range at an altitude of 1000 ft with a significantly reduced range at 1500 ft. The observation of longer ranges at 1000 ft was substantiated by the helicopter pilots in debriefs after each flight. The reason for this observation was not clear. It was conjectured that this could simply be due to the geometry of the approach, to the structure of the intervening atmosphere, or to the characteristics of the target or the sensor. To evaluate these possibilities a model was built which included these effects.

Extinction Model

The effect of atmospheric stratification on the extinction was modeled with a simple profile of atmospheric extinction . The atmosphere is assumed to consist of two layers; a lower layer of high extinction, and an upper layer of less extinction. This corresponds to the mixed layer models (Deardorff 1976, Roll, 1965, Hsu, 1988). The vertical behaviour is described using a parametrization of Moore(1991), originally applied to horizontal variation of sea surface temperature, but found to be reasonably useful for this application. This parametrization has the advantage of not only describing the vertical profile reasonably well, but also of being integrable. The vertical profile of the extinction coefficient , $k(z)$, is ,

Figure 2. Extinction coefficient model for different parameter values.

$$
\begin{aligned}
k(z) &= k_{sfc} + \left(k_{aloft} - k_{sfc} \right) \left[1 + \frac{2}{\pi} \left(\arctan\left\{ \frac{z - z_i}{z_e} \right\} \right) \right] / 2 \\
&= \frac{k_{sfc} + k_{aloft}}{2} + \frac{k_{aloft} - k_{sfc}}{\pi} \arctan\left\{ \frac{z - z_i}{z_e} \right\},
\end{aligned}
\tag{1}
$$

where k_{sfc}, k_{aloft} are the surface and aloft volume extinction coefficients respectively, z is altitude, z_i is the altitude of center of the transition, and z_e is the depth of the transition zone. An example of the dependence of the volume extinction coefficient for different parameter values is shown in Figure 2.

The total extinction over a slant path S, from the surface to a given altitude Z is

$$
\begin{aligned}
\sigma &= \int_0^S k(z)ds \\
&= \frac{1}{\mu} \int_0^z k(z)dz,
\end{aligned}
\tag{2}
$$

where μ is the depression angle from the horizontal at the sensor. For a given altitude and depression angle, the total optical extinction can be evaluated in closed form as,
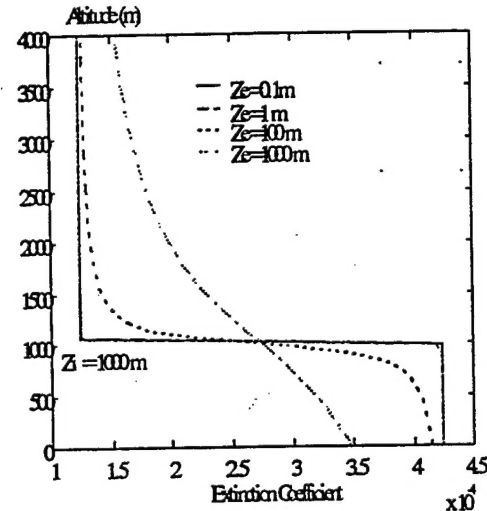
$$\sigma = \frac{k_{sfc} + k_{alft}}{2}\sqrt{R^2 + Z^2} + \frac{k_{alft} - k_{sfc}}{\pi}\frac{\sqrt{R^2 + Z^2}}{Z} *$$

$$\left[(Z - z_i)\arctan(\frac{(Z - z_i)}{z_e}) - z_i\arctan(\frac{z_i}{z_e}) + \frac{z_e}{2}\log\left(\frac{1 + \left(\frac{(Z - z_i)}{z_e}\right)^2}{1 + (\frac{z_i}{z_e})^2} \right) \right] \tag{3}$$

The detection range is defined for our purposes as that range where the total optical depth exceeds a given threshold. A common criterion is the 5% contrast threshold (Lloyd, 1975), where the detection range is defined as the separation where total loss of signal is 5%, or,
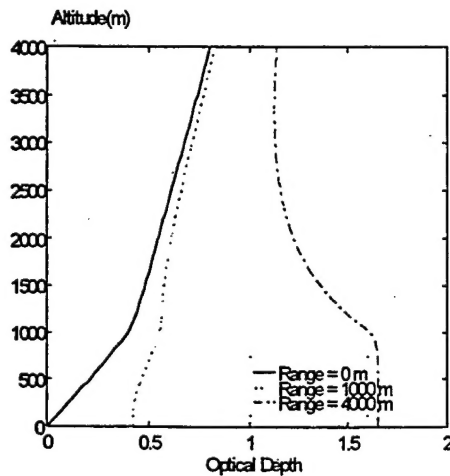
$$R = \frac{3.912}{\sigma}. \tag{4}$$

Figure 3. Optical depth as function of range for several surface range values.

Using the range model defined by equations (1) and (2), the calculated optical depth for a given range, R, is obtained as a function of altitude for different horizontal ranges between target and detector. For a detector directly overhead (R=0), the extinction increases most rapidly in the lower layer, and then decreases more slowly in the upper layer. At any value of range, the extinction increases as a function of altitude in the lower layer, but then decreases in the lowest part of the upper layer. This occurs because a part of the slant path in the lower layer is replaced by part of the path being in the upper layer, decreasing the total extinction. The altitude dependence of the optical depth is shown for several values of ground range in Figure 3.

The detection range also depends on the cross sectional area of the target presented to the detector. For a target of significant width, the presented area thus increases with altitude to a maximum, and then decreases. In this model, the optical depth required for detection is scaled by the ratio of presented area at a particular depression angle to the presented area at the surface. For a target of width W, length L, and height H, the effective cross section at a depression angle θ is given by

$$\sigma = \sigma_0 \frac{H\cos\theta + W\sin\theta}{H}. \tag{5}$$

Sensitivity

The model of equations (3) and (4) is used to describe the sensitivity of the detection range to the details of atmospheric structure and to the characteristics of the sensor. The most general characteristic of the detection range behaviour with altitude is that as altitude increases, range increases because of the increased presented area. As the altitude increases farther, the range starts to decrease because of the increase in total optical depth from the increased altitude. This general behaviour is modified by the stratification, the difference between surface and aloft extinction, and the sensitivity of the detector.

The dependence on kind of stratification is seen from the change in z_e, the depth of the transition zone. The gradual stratification is accompanied by a more abrupt increase in range at the transition zone. The range also exhibits a maximum with height, but the abrupt stratification exhibits a slightly longer detection range. This is due to the shorter path in the high extinction zone for the abrupt stratification by comparison to the smoother profile. The dependence on stratification is shown in Figure 4.

The dependence on surface extinction is shown in Figure 5. With higher surface extinction, the detection range shows a pronounced maximum in the range. With a lower extinction, the profile is more diffuse, without a clear maximum in range with altitude.

The dependence on receiver sensitivity can be shown by varying the optical depth necessary for detection. Figure 6 shows the changes as this optical depth is changed by 30%. The less sensitive receiver has a more pronounced maximum in range with altitude. The more sensitive receiver has less altitude dependence, with a range of altitudes where the range is not changing significantly.

Conclusions

The optimal choice of altitude for using a FLIR sensor depends on the environment, as well as operational and equipment conditions. The geometry of the detection, determined by the size of target, separation of target and sensor, and the sensitivity of the sensor are generally modified by the specifics of the intervening atmosphere. Operational observations and theoretical modeling indicate that atmospheric stratification, strength of extinction, and the sensitivity of the sensor modify the optimal altitude for best system performance. The model shows that the stratification of the atmosphere modifies the optimal altitude by increasing the best altitude, but resulting in a longer altitude range than an unstratified profile. The relative volume extinction at the surface and aloft affect the shape of the detection range profile. With a higher surface extinction, the optimal detection range is restricted to a smaller range of altitudes by comparison to the lower surface extinction. Sensor sensitivity exhibits similar results, in that
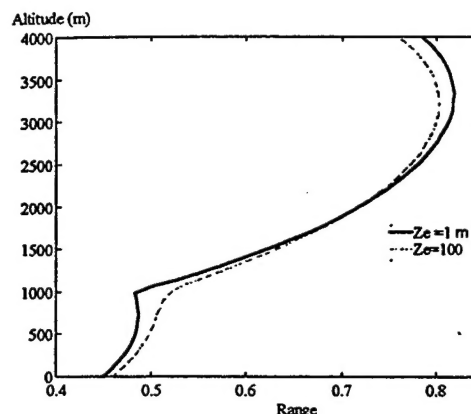

Figure 4. Vertical detection range profile for slight and strong stratification. Range scale is in non-dimensional units.
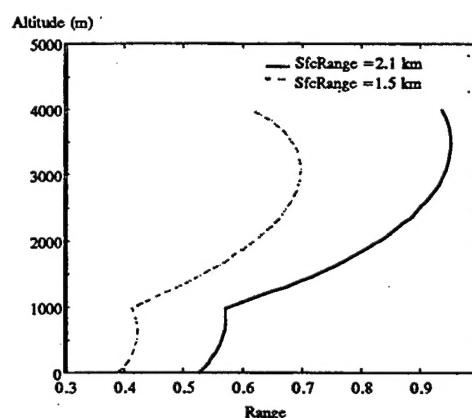

Figure 5. Detection range dependence on surface extinction (expressed as range).
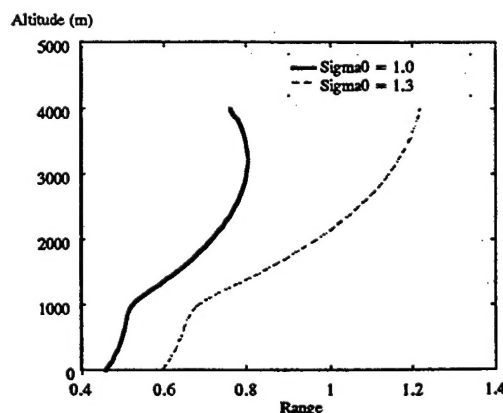

Figure 6. Detection range profiles for different receiver sensitivities.

the more sensitive system, has a less well defined optimal altitude than the less sensitive system.

Acknowledgments

References

Deardorff, J.W., 1976: "On the entrainment rate of a stratocumulus-topped mixed layer," Quart J. R. Met. Soc., **102**, 563-582.

Hsu, S. A., 1988: "Coastal Meteorology," Academic Press, New York. 260 pp.

Lloyd, J. M., 1975:"Thermal Imaging Systems," Plenum Press, New York, 456 pp.

Moore, G. W. Kent, 1991:"Frontogenesis in the presence of surface heating," J. Atmos. Sci. **48**, 63-75.

Roll, H. U. , 1965: "Physics of the Marine Atmosphere," Academic Press, New York, 276 pp.